



Modeling wind waves and morphodynamics near the Corte Madera salt marsh

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1. Introduction

1.1 Corte Madera area

The shore area in the Corte Madera embayment contains intriguing morphodynamic features (Figure 1). The salt marsh just in front of the primary dike (Figure 2a) is vegetated and cross-cut by tidal creeks (Figure 2b, c, d). The marsh floods regularly at high tidal water levels. Seaward, the salt marsh is protected by low (~ 1 m above mean sea level) levees (Figure 2f). The levee system shows breaches allowing the tide to enter the marsh via major tidal creeks. Erosion of the salt marsh by wind waves occurs close to the inlet breaches (Figure 2e, f). The mudflat starts just in front of the levees and slowly lowers until it connects to Central Bay with high prevailing tidal currents draining and flooding North Bay and the Delta. Corte Madera Creek discharges northwest of the Salt Marsh and supplies sediments during occasional creek flow events (maximum up to $50 \text{ m}^3/\text{s}$). Another sediment source comes from the Bay, especially during high flow of the Sacramento River.



Figure 1 Corte Madera area

(a)



(b)



(c)



(d)



(e)



(f)



Figure 2 (a) Primary dike protection of Corte Madera (left shows start of salt marsh, (b) Main tidal channel draining the marsh, (c) Muddy, secondary channel draining the marsh (at low tide), (d) Spartina at the salt marsh, (e) Salt marsh erosion at a breach inlet, (f) Remnants of the old levee system. A breach inlet is in the foreground.

Future changes to the system related to sea level rise and a decrease sediment supply will have an impact on the Corte Madera Bay. However, it is difficult to assess expected changes, since only limited system knowledge is available. Data regarding wind waves, bathymetry, bed composition, sediment supply, and salt marsh growth were collected during this project, but are limited. Model development may help to understand physical processes and adaptation timescales of this system so that expected changes can be mitigated and managed properly

1.2 Study objectives

The objectives of this study are to

- calibrate and validate the SWAN wave model against measurements;
- compare SWAN wave model results with results from the highly schematized WHAFIS model (discussed in the main report);
- assess the impact of future scenarios on wind wave characteristics with the calibrated SWAN model;
- explore possibilities of morphodynamic predictions with Delft3D and SWAN software;

1.3. Model setup

We developed a 2D model to reproduce the wave measurements by Lacy and Hoover (2011) taken during January 22 to March 24, 2010. We developed a grid with a spatial resolution of 5 m to describe channels on the Corte Madera salt marsh (Figure 3c). To generate trustworthy tidal forcing conditions we nested this model in a lower resolution intermediate model (Figure 3b, 50 m spatial resolution), which was nested, in its turn, in a larger low resolution (100-200 m) model covering the full San Francisco Bay area (see the appendix of Van der Wegen et al. 2011 for a closer description of this large model). In this way, we were able to generate tidal forcing of the high resolution Corte Madera model at any moment in time by applying measured tidal boundary conditions at Point Reyes. The SWAN model with a grid similar to the Corte Madera grid (Figure 3c) was integrated with the Delft3D FLOW model to receive the water depth and velocity profiles necessary to model wind wave characteristics.

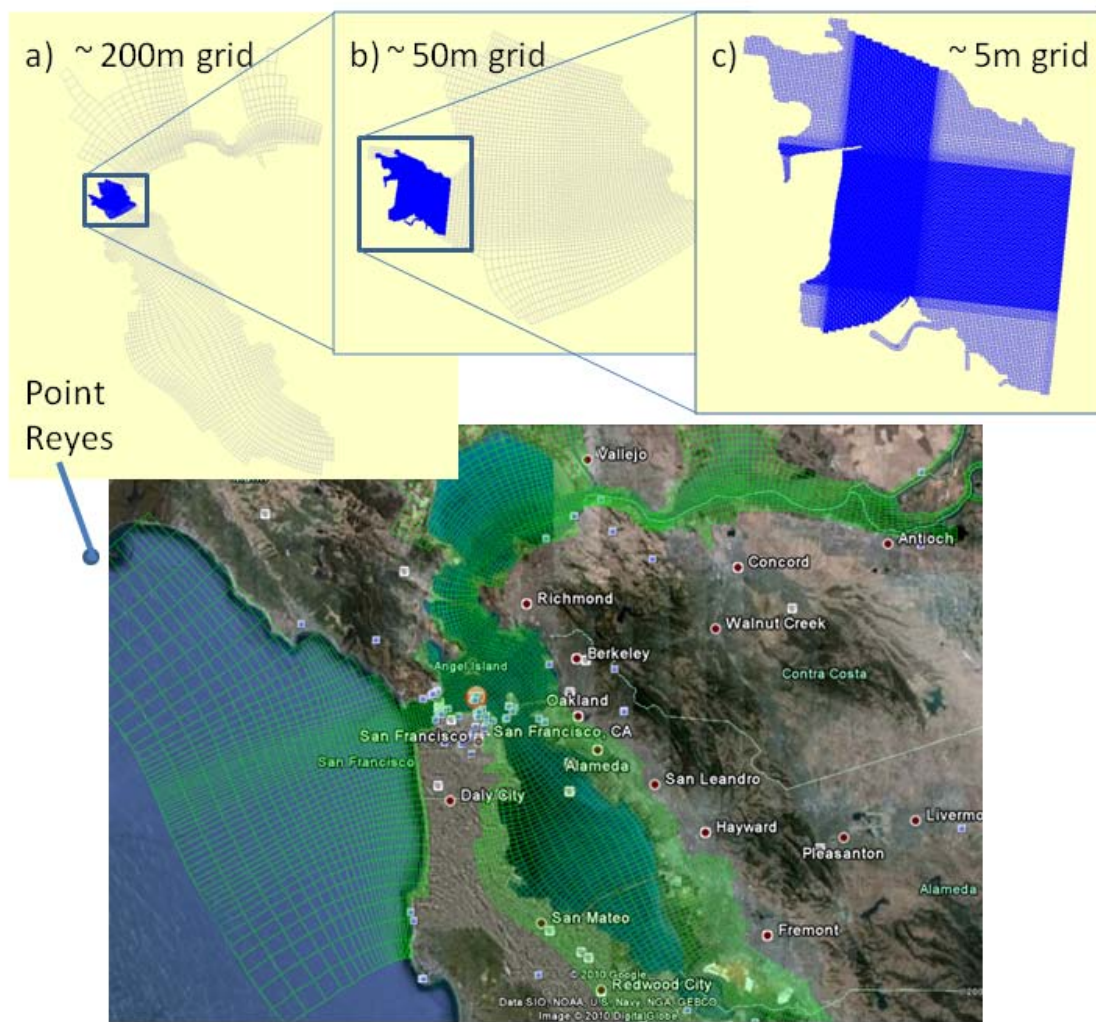


Figure 3 Model grid and wave grids (a,b,c)

2. Model results

2.1. Comparison to measurements

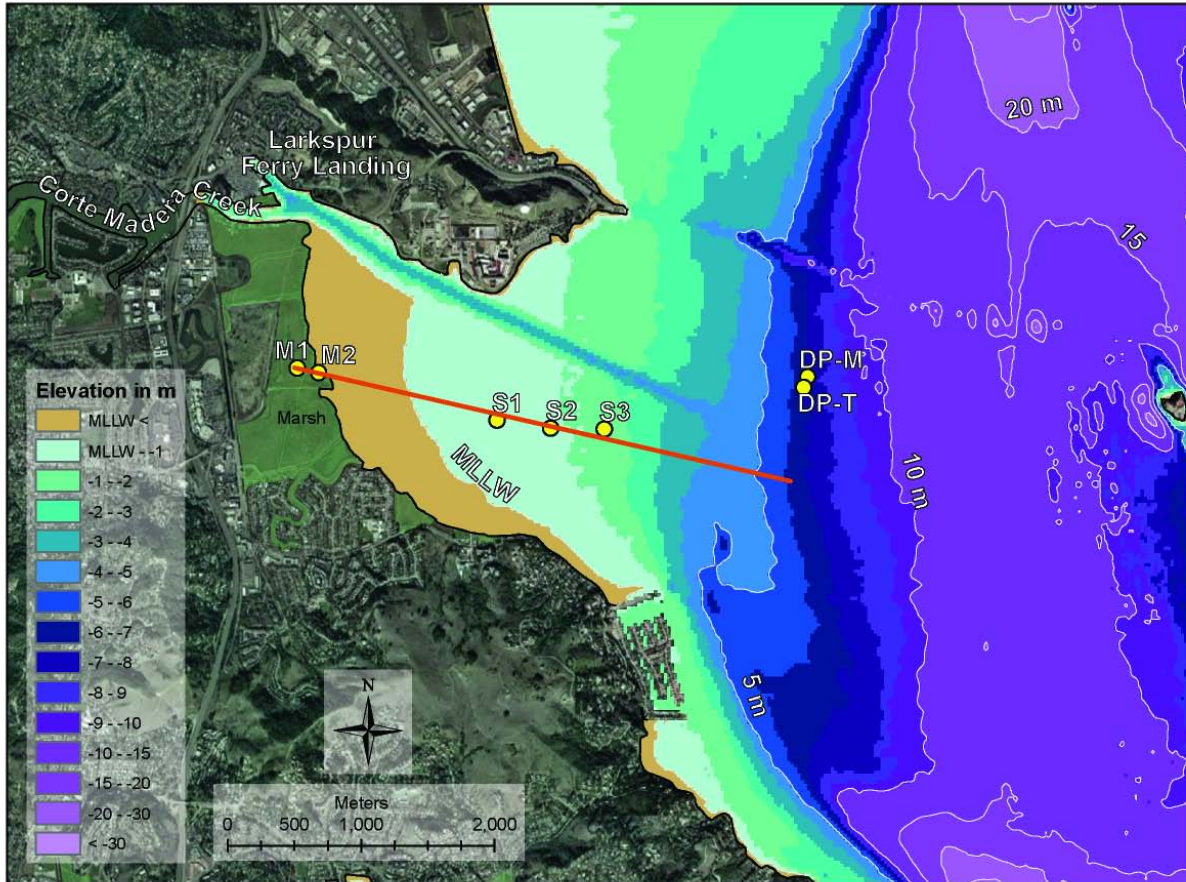


Figure 4 Location of measurements

Figure 4 shows the locations of the measurement stations. Lacy and Hoover (2011) give details of the equipment used. The January 22 to March 24, 2010 experiment included days with significant wave action (Figure 5). Figure 6 provides wind data. We focus on a period between February 5 and 7 (red circles) for calibration and a period between February 22 and 25 (green circles) for validation of the calibrated model. The modeled waves are purely wind generated (no wave boundary condition). We applied wind conditions obtained from Richmond meteorological station RCMC1 provided at 10 m above the station level (which is 15.6 m above MSL) <http://www.ndbc.noaa.gov/>.

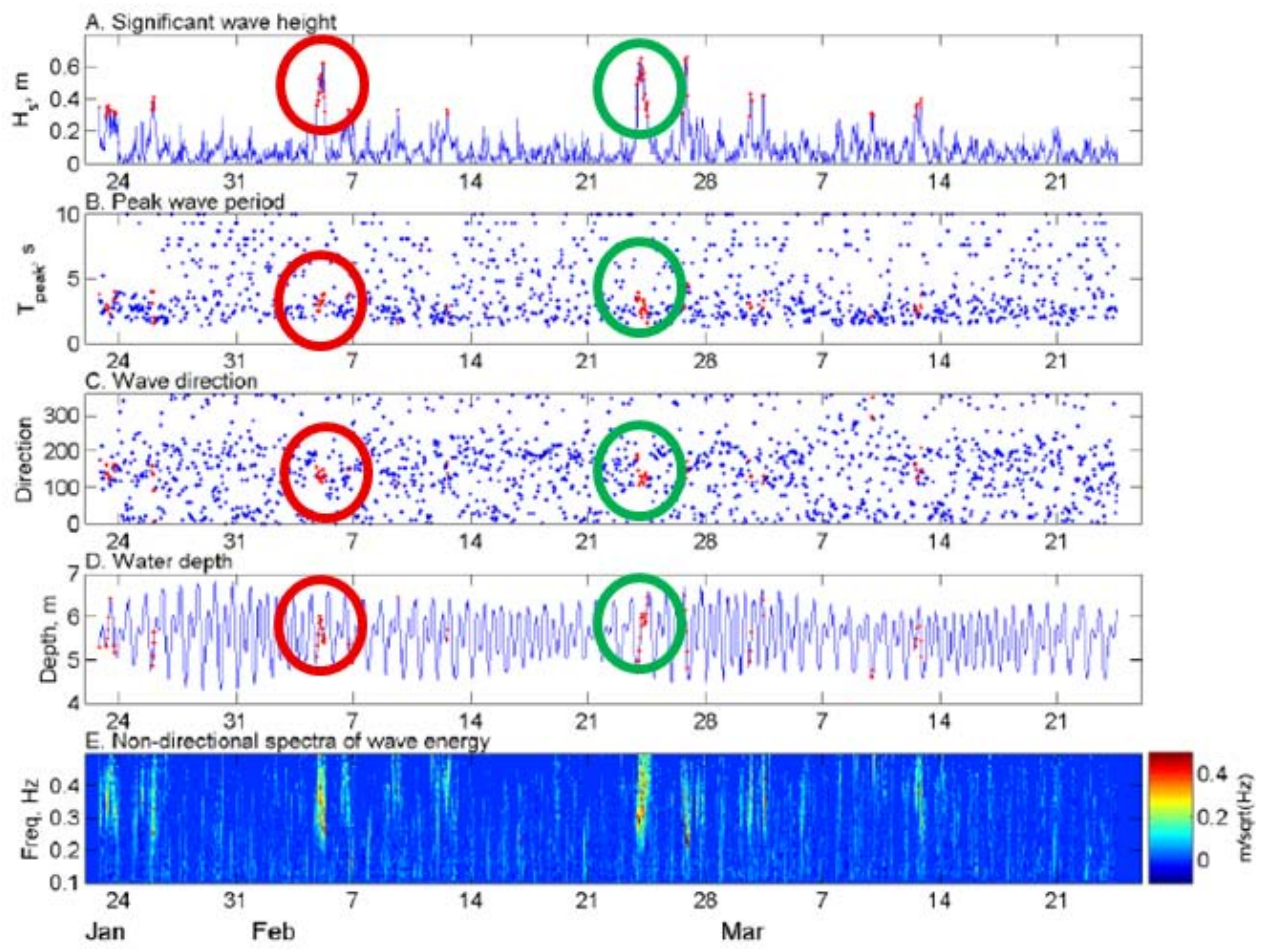


Figure 5 Wave data during period of data calibration (after Lacy and Hoover, 2011)

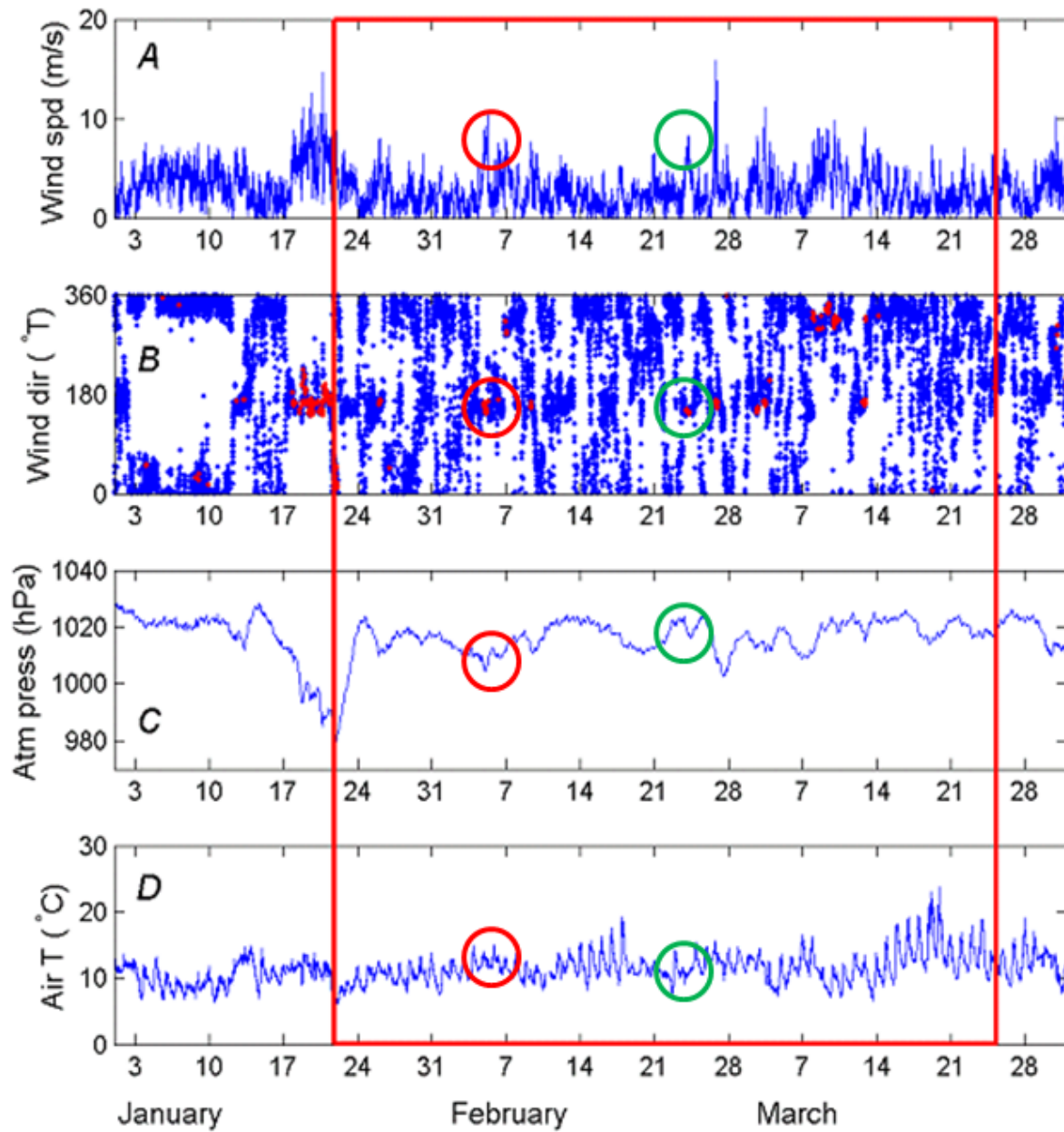


Figure 6 Wind and pressure data during period of data calibration (after Lacy and Hoover, 2011)

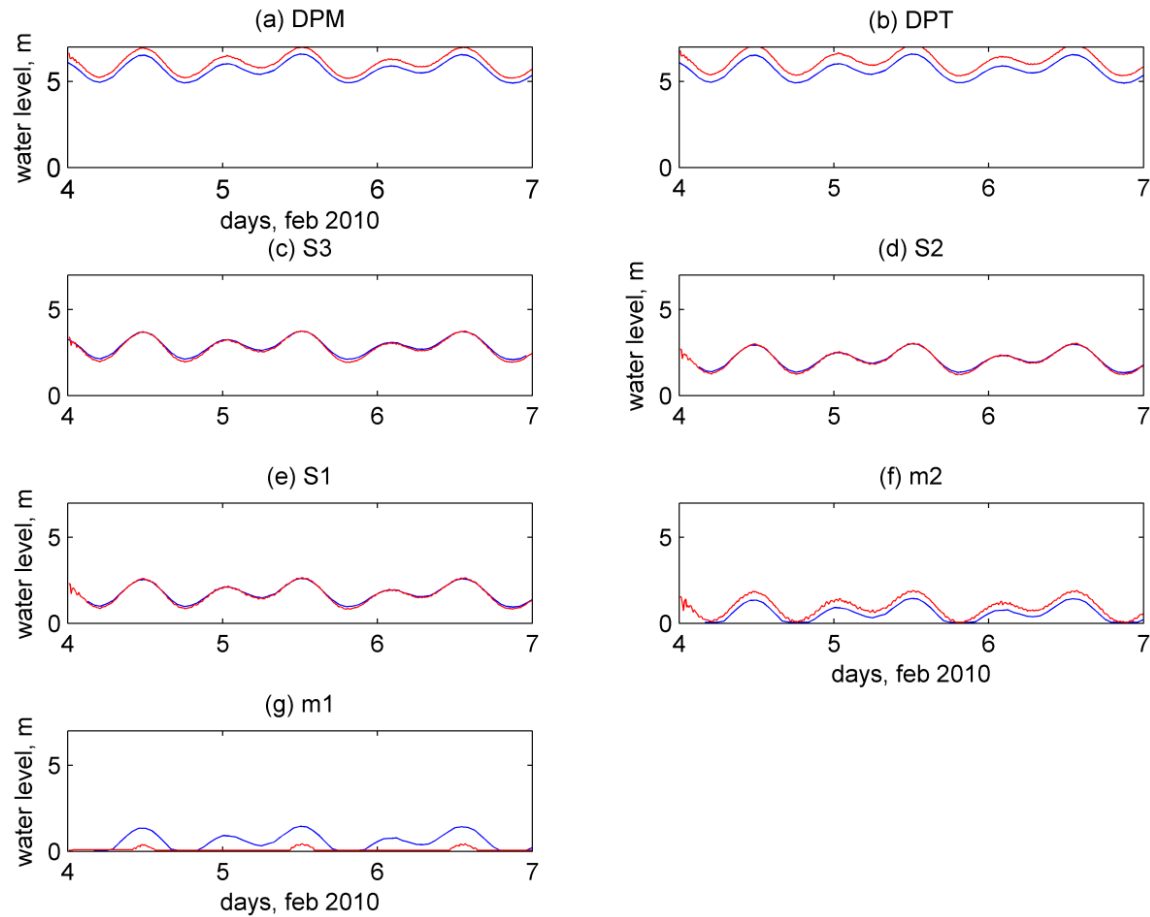


Figure 7 Measured (blue) and modeled (red) water depth at different measurement stations for beginning of February 2010 (red circles in Figure 5).

Water levels are well reproduced by the model (Figure 7) although slight deviations are observed that are probably due to deviations between the real and the model bathymetry. These are attributed to the timing of bathymetric measurements compared to the wave measurements, the different ways of taking measurements (equipment on the bed versus echo sounding from a vessel) and the bathymetric interpolation procedure of the model.

When applying the default model settings, the model reproduces the significant wave height and the wave attenuation towards the salt marsh fairly well (Figure 8). The model underestimates the peak wave period (Figure 9) and the orbital velocities (Figure 10) significantly. This is a known deficit deficiency of the SWAN model when applied to (very) shallow conditions and small wave heights.

Figure 11 shows the significant wave height for the validation period. The model performance is comparable to the calibration period, although the model slightly underestimates wave heights at the deeper locations. Other parameter comparisons (not shown) are similar for the calibration period as well.

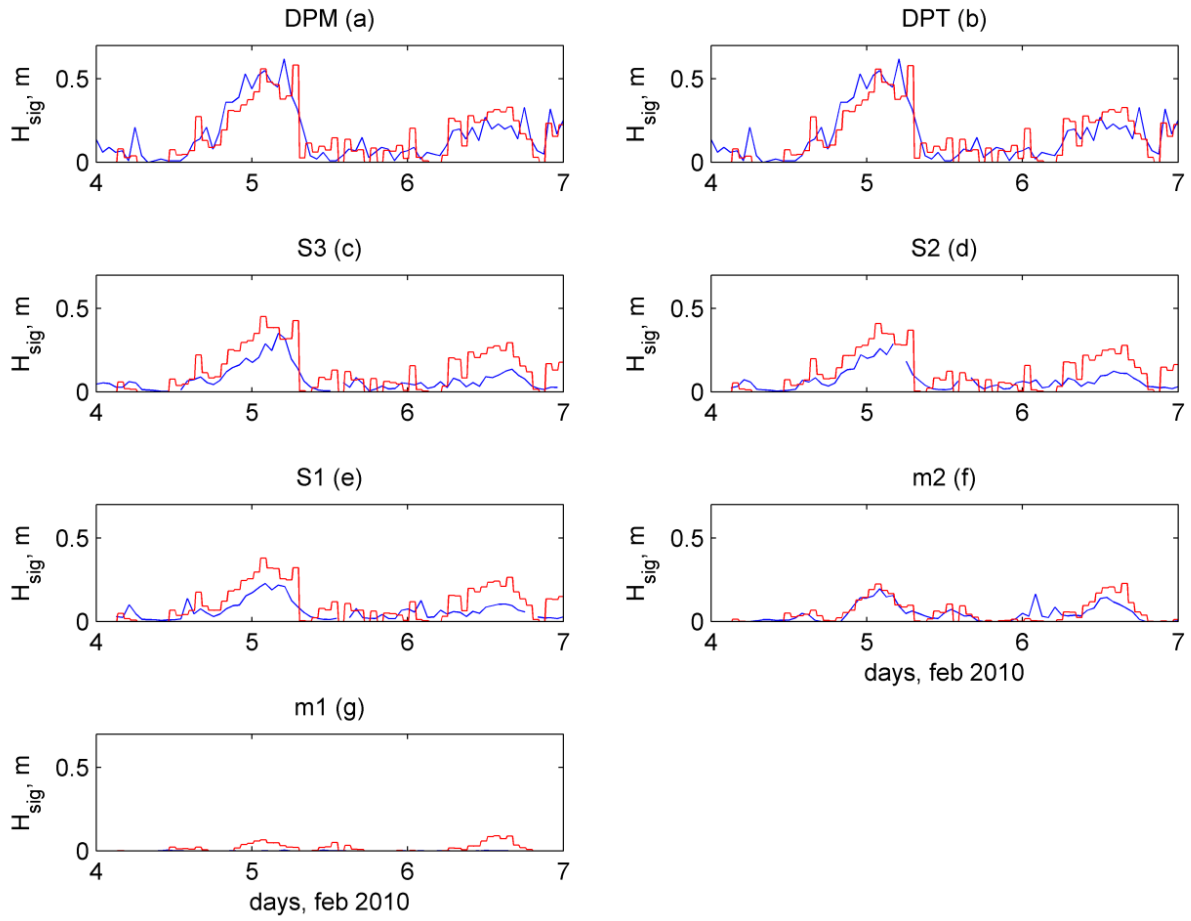


Figure 8 Measured (blue) and modeled (red) significant wave height at different measurement stations for beginning of February 2010 (red circles in Figure 5).

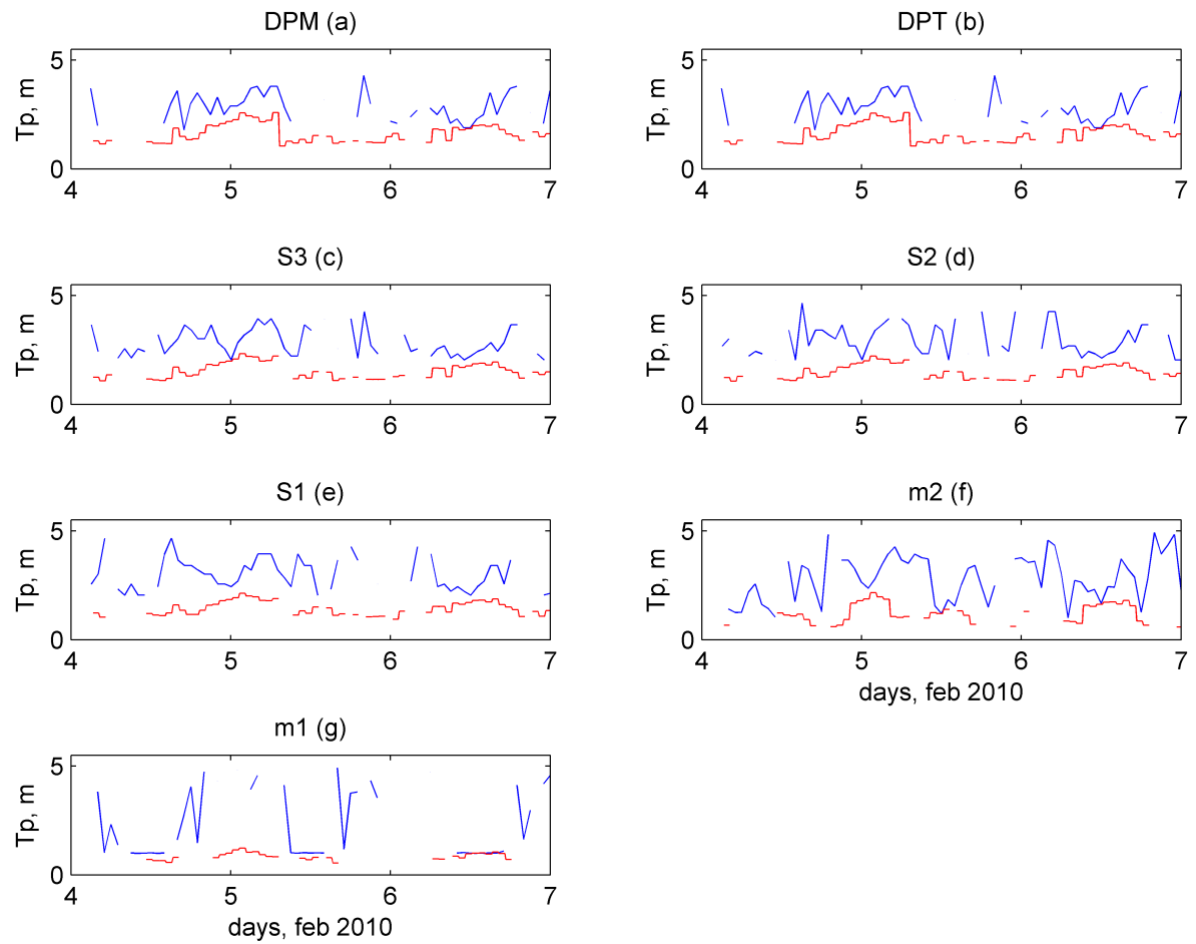


Figure 9 Measured (blue) and modeled (red) peak wave period at different measurement stations for beginning of February 2010 (red circles in Figure 5). (Unrealistic) measured periods above 6 seconds are truncated.

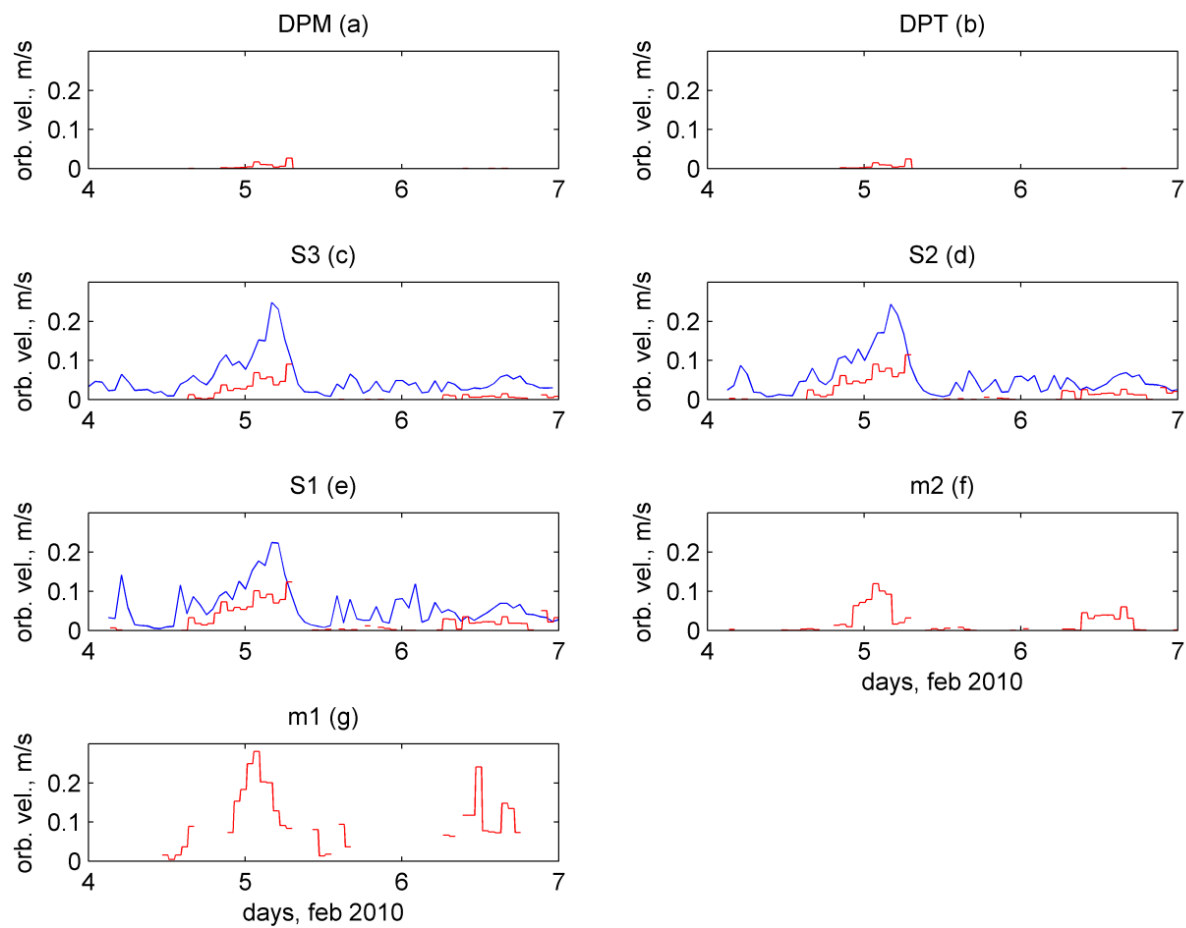


Figure 10 Measured (blue) and modeled (red) orbital velocity at different measurement stations for beginning of February 2010 (red circles in Figure 5).

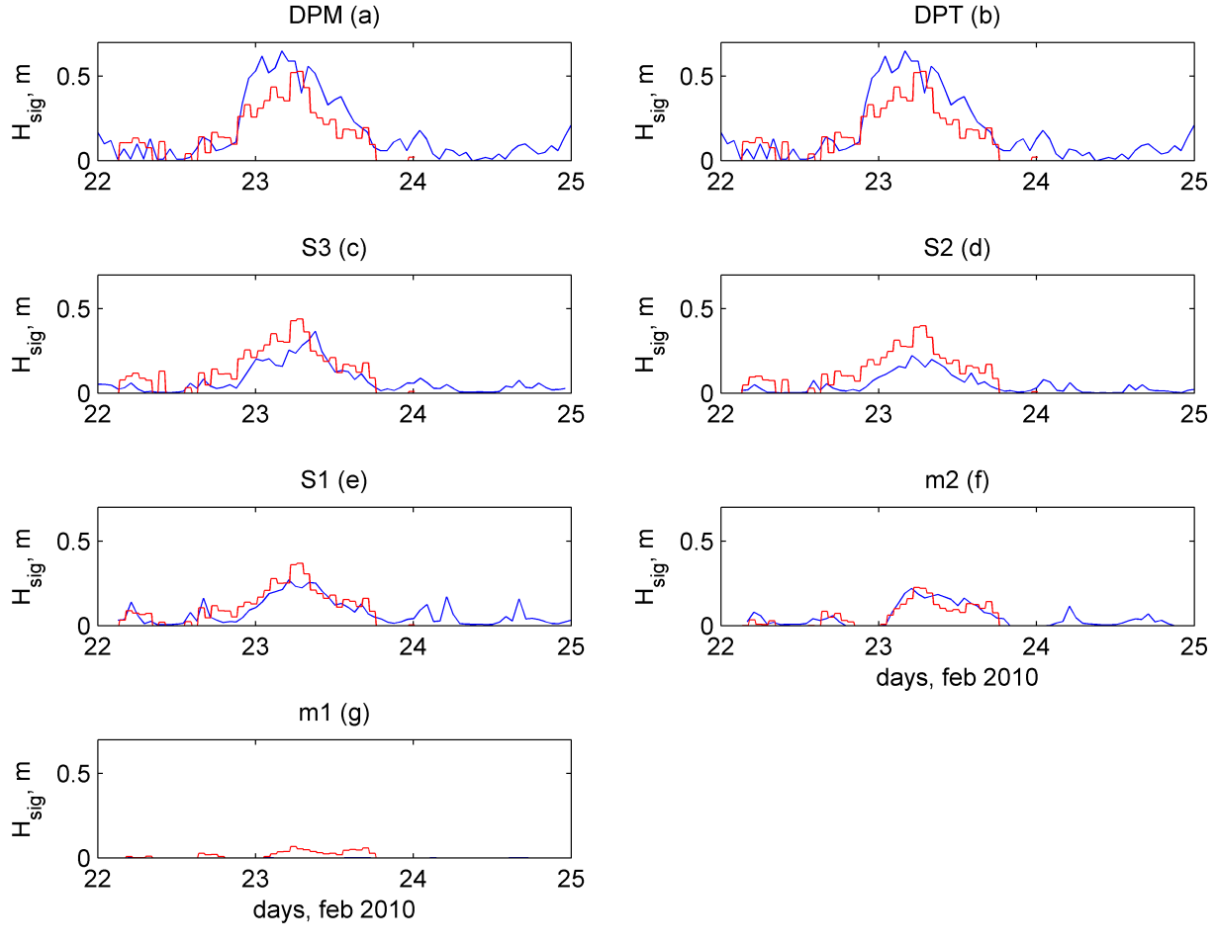


Figure 11. Measured (blue) and modeled (red) significant wave height at different measurement stations for end of February 2010 (green circles in Figure 5).

2.2. Scenarios

To assess the impact of a number of parameters on wave heights on the salt marsh and mudflat in the Corte Madera area we carried out a rudimentary sensitivity analysis. The parameters are water level, wind velocity, presence of levees, vegetation cover, mudflat accretion and salt marsh accretion.

The standard run applies a vegetation cover on the salt marsh with a vegetation height of 0.6m, a vegetation diameter of 0.013m, 215 stems per square meter, and a vegetation drag coefficient of 0.5 representing the vegetation cover shown in Figure 11. Furthermore, the standard case applies a water level of about 1.8 m (~6 ft) above NAVD88, which approximates one of the most extreme tide induced water levels during a year. The geodetic vertical datum of NAVD88 closely approximates the tidal datum of mean lower low water (MLLW) in Corte Madera Bay. VDatum conversions within our study area show that the datum of MLLW is, on average, 3 cm below the datum of NAVD88. The choice of 1.8 for the

standard case is an underestimate because, in reality, the presence of wind and waves may increase this maximum level. We set the wind conditions at 9 m/s (20mph) from the east. Typically, we would apply a combination of maximum water level and wind conditions with a probability of exceedance of (for example) 1/100 year. However, a full probabilistic analysis of the area is complex due to the highly variable tidal and wind conditions and does not exist yet.



Figure 12 Pickle weed vegetation at the Corte Madera salt marsh.

Therefore, we choose extreme conditions for the water level and wind field based on observations. The results give a qualitative impression of the potential importance of different parameters. The study may thus act as guideline for future, full probabilistic assessments.

In this analysis we further focus on a transect covering the mudflat and the salt marsh as defined by the red line in Figure 12. The figures present the bed level (in black), the water level including wave and wind setup (in red). The blue line gives the significant wave height with the water level as a reference. Note that this does not reflect a realistic water level, just the elevation of the wave crests. Subtracting the red line from the blue line gives the significant wave height.

Figure 14 shows 6, 7, 8, 9, and 10 ft water levels (in red) as well as the combined model-generated wave heights and water levels (in blue) for these scenarios. These runs excluded the secondary levees at the interface between marsh and mudflat. The wind causes a small water level setup on the marsh (~4cm for 20 mph wind speeds). The major wave height decrease is at the interface of mudflat and marsh,



Figure 13 Transect (red line) for further analysis

although significant attenuation takes place over the marsh as well. The wave height increases slightly for higher water levels at the seaward boundary (wave height is the difference between the red and blue line in Figure 14). On the salt marsh waves are hardly present for 6ft water level, but are about 1 ft at the landward end of the marsh for the 10 ft water level. Doubling the wind speed leads to slightly higher water levels (~6cm) and larger waves along the transect. Wave height increase is about 70% at the seaward boundary and about 20% at the landward end for 10ft water levels.

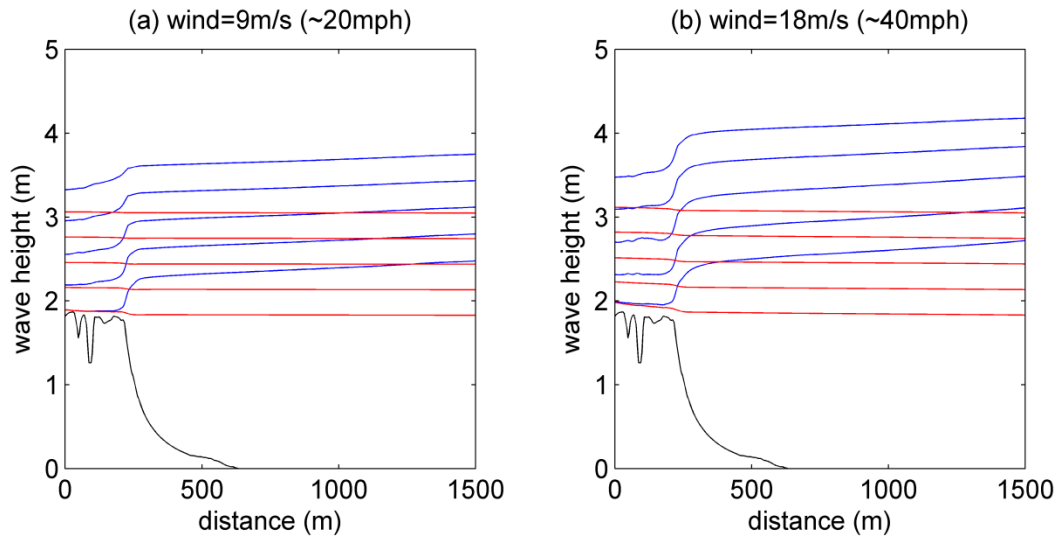


Figure 14. The impact of water levels. Bed level excluding levee (black), water level (red) and water level + wave height (blue) for scenarios of 6, 7, 8, 9 and 10 ft NAVD water level. (a) With easterly wind of 9m/s (~ 20 mph) and (b) with easterly wind of 18 m/s (~40 mph).

Once the (existing) levees are included, the wave height decreases considerably at the levee's location and for approximately 30 m inland (Figure 15). The levee may seem to block water from the seaside in this figure, but actually that water enters the marsh in the 2D model via small inlets. Remarkably, when the water level is at 9 ft NAVD, the wave height over the landward half of the salt marsh (distance 0-75 m) hardly changes when the levee is included. This suggests that, at that location, the wave height is hardly a function of the incoming wave height and levee, but rather that the wave is locally generated by wind over the salt marsh. The horizontal blue line on the salt marsh suggests that there is a local equilibrium between the gain of energy from wind and energy dissipation due to bed friction and vegetation. Wave heights increase for higher water levels and higher wind velocities.

The vegetation cover on the salt marsh has a significant effect on the wave height at the landward salt marsh end. With a water level of 10 ft the wave height almost doubles once vegetation is excluded (Figure 16a), although the effect is smaller for higher wind velocities (compare Figure 16a and b).

The level of the mudflat is an important parameter for the local wave height. It may even be argued that the future fate of the Corte Madera salt marsh is a major function of the mudflat level. Morphodynamic developments of the mudflat will depend on the sediment supply from Corte Madera Creek (probably to a limited extend as will be argued in later sections), but mainly from the sediment supply from the North Bay and Delta during high river flow conditions. Here we present the case that the mudflat level follows the rise in water level (Figure 17). The result is that wave heights on the mudflat will remain the same for different water levels (and mudflat levels), since the water depth does not change, i.e. subtract the red line from the thick blue line in Figure 17. When mud flat level rise is not considered (thin blue lines), wave heights are larger. This effect is more important for higher water levels and larger waves.

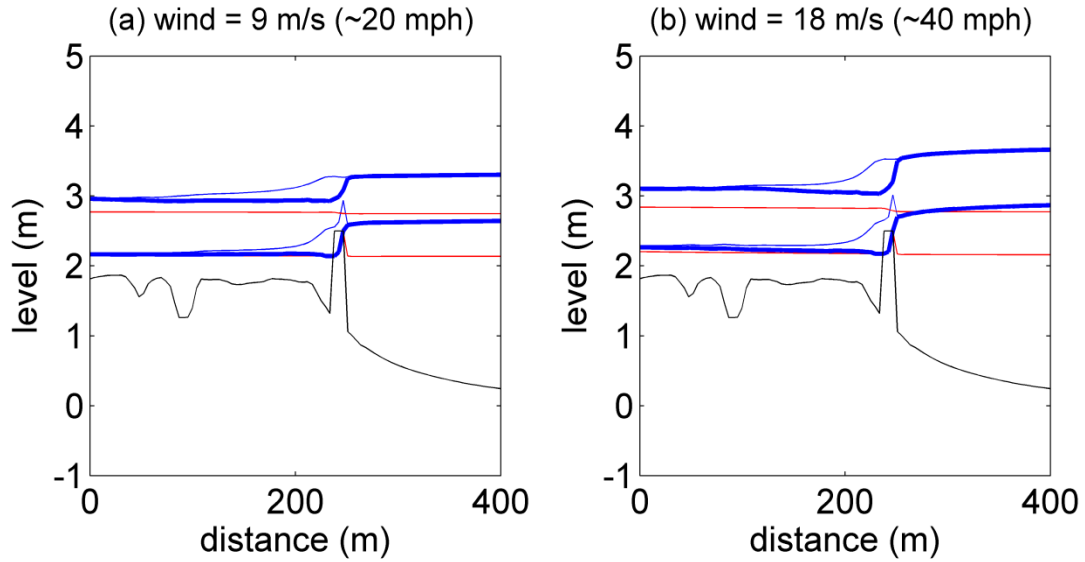


Figure 15. The impact of levee presence. Bed level including levee (black), water level (red) and water level + wave height (blue) for scenarios of 7 and 9 ft NAVD water level. (a) With easterly wind of 9m/s (~ 20 mph) and (b) with easterly wind of 18 m/s (~40 mph). Thick blue line includes levee, thin blue line excludes levee.

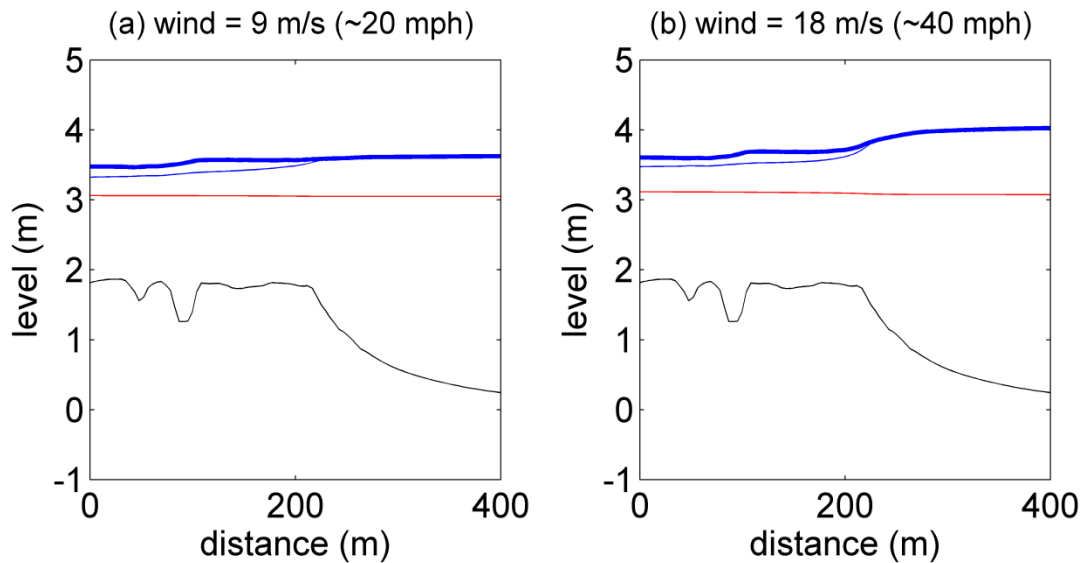


Figure 16. The impact of vegetation presence. Bed level (black), water level (red) and water level + wave height (blue) for scenario 10 ft NAVD water level. (a) With easterly wind of 9m/s (~ 20 mph) and (b) with easterly wind of 18 m/s (~40 mph). Thick blue line excludes vegetation, thin blue line includes vegetation.

However, because the levee controls the height of waves on the marsh, there is no change in wave height on the marsh as a function of the mudflat elevation.

Another potential development is that the salt marsh level increases, keeping pace with the increase in sea level rise by sediment accretion, whereas the mudflat level remains constant. Figure 18 shows that this leads to insignificant waves on the marsh as a result of very small water depths.

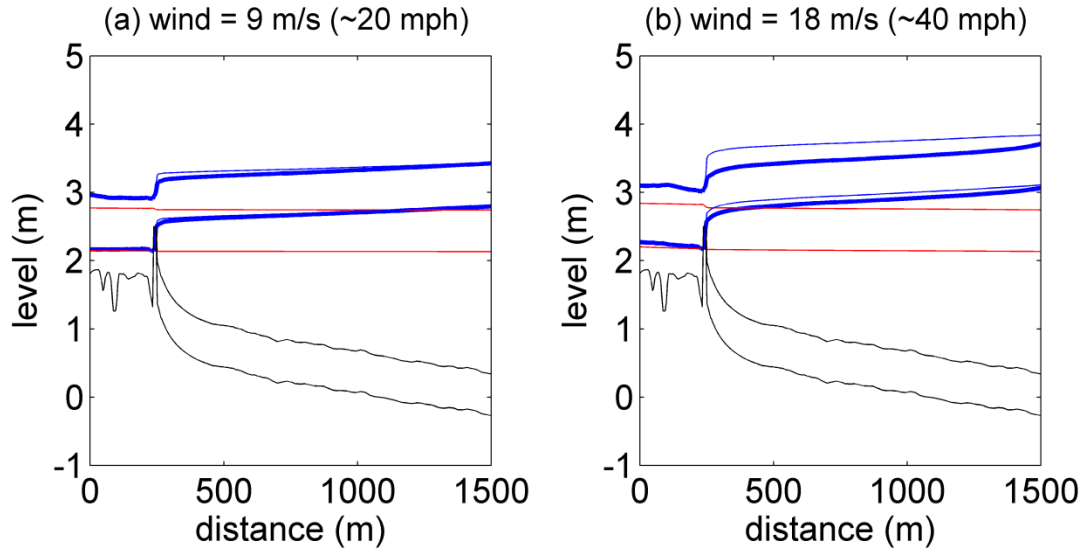


Figure 17 The impact of mud flat level increase. Bed level including levee (black), water level (red) and water level + wave height (blue) for scenario 7 and 9 ft NAVD water level. (a) With easterly wind of 9m/s (~ 20 mph) and (b) with easterly wind of 18 m/s (~40 mph). Thick blue line include rise of mudflat bed level, thin blue line exclude this effect.

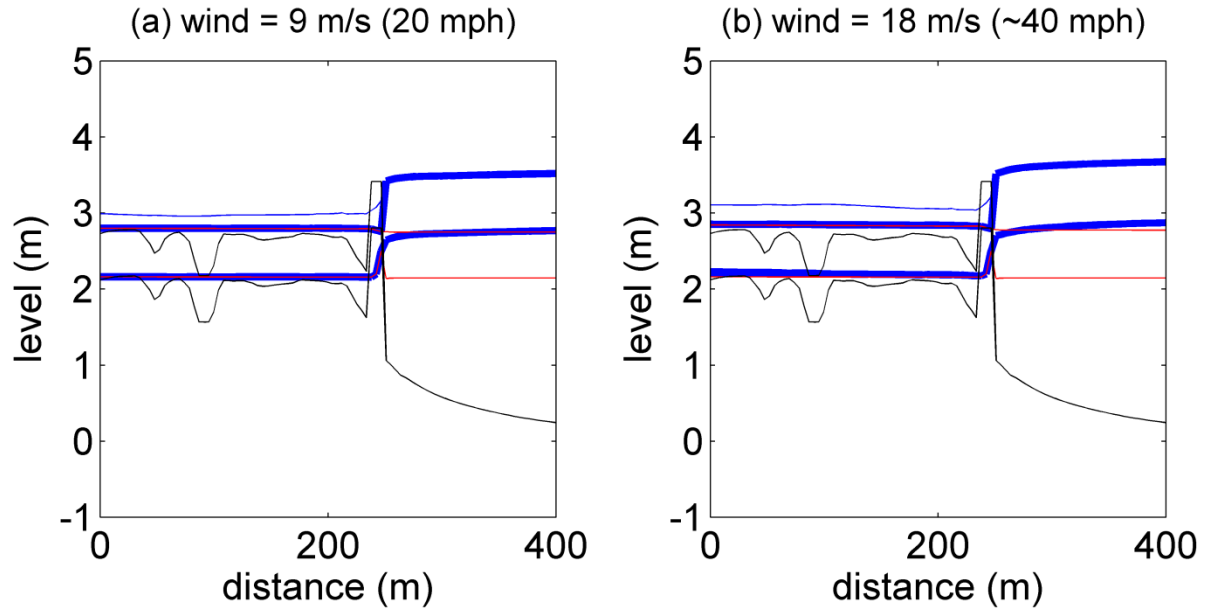


Figure 18 The impact of salt marsh level increase. Bed level including levee (black), water level (red) and water level + wave height (blue) for scenario 7 and 9 ft NAVD water level. (a) With easterly wind of 9m/s (~ 20 mph) and (b) with easterly wind of 18 m/s (~40 mph). Thick blue line include rise of salt marsh level, thin line excludes this effect.

2.3. Morphodynamic Modeling

This section reports the results of model runs including sediment transport and bed elevation change in the Corte Madera Bay. The runs indicate where sediment from different sources (the Creek or the Bay) will settle in the Corte Madera Bay under highly schematized model input. These preliminary runs will help to address the possibility of full, morphodynamic runs that are able to predict morphodynamic development of the mud flat and marsh over decades.

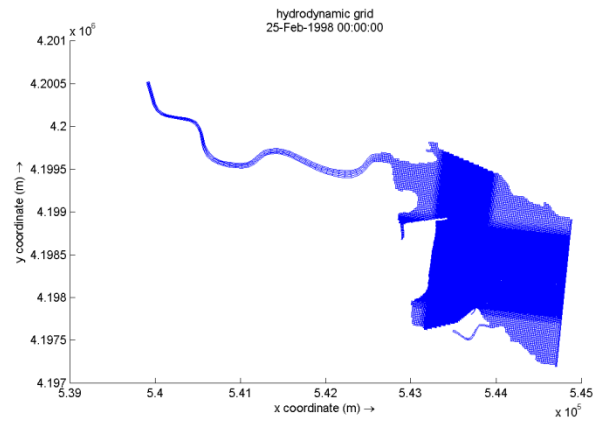


Figure 19 Grid for morphodynamic runs

2.3.1 Model setup

The model setup is slightly different from the wave runs described in previous sections. The grid is extended to include Corte Madera Creek (Figure 18). Table 1 describes the specifications. The hydrodynamic forcing was by river discharge ($10 \text{ m}^3/\text{s}$ with SSC of 300 mg/l , which is higher than the Creek would flow and a larger sediment supply than for much of the year) at the Creek and tidal water level forcing along the eastern boundary (with SSC of 100 mg/l). The following USGS website provides detailed information on discharge distribution in the Creek:

http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11460000.

We defined three sediment size fractions with equal characteristics to trace the origin of the sediments (from the Creek, the Bay and from the Corte Madera Mudflat). Although some of the sediment characteristics were measured during this project (shear stress, erosion factor), their values may vary in reality depending on the location and timing (i.e. due to seasonally fluctuating bio-mass availability). Fall velocity was not measured. Fall velocity could also not easily be derived from sediment particle size in the bed, since suspended mud was probably transported as multiple particle flocs. The modeled value was formed by earlier modeling work on morphodynamic development in San Pablo Bay, which is almost adjacent to Corte Madera (Van der Wegen et al., 2011). Wind was constant generating waves of about 0.2-0.5 m on the mudflat depending on the tidal water level. Vegetation was defined on the salt marsh as described in the previous sections. The model run duration was 1 month (Figure 19). One other model run mimicked the impact of sea level rise by adding 1 m on top of the forcing water level. The Creek and Bay sediment was delivered via the boundaries to the model domain during the model run. The CM sediment was available everywhere in the domain. Sediment could settle and erode during the

run anywhere in the model domain. Erosion and sedimentation magnitudes were enhanced by a morphological factor of 12 so that the model run represents 1 year of morphodynamic development.

Table 1 Specifications for morphodynamic runs

Hydrodynamic time frame	Jan 27-Feb 27
Morphological factor	12
Morphodynamic time frame	1 year
Creek discharge	10 m ³ /s
Tidal constituents applied for forcing	M2, O1, K1, S2, N2, M4
wind	10 m/s easterly wind
Sediment: falling velocity	0.25 mm/s
Sediment: critical shear stress for erosion	0.35 N/m ²
Sediment: erosion factor	10 ⁻⁴ kg/m ² /s
Sediment: dry bed density	1200 kg/m ³

2.3.2 Model results

Figure 21 and Figure 22 show the 1 month morphodynamic developments with and without imposing sea level rise (SLR), respectively. The most striking observation is the major sedimentation in the dredged access channel. Secondly, SLR leads to much more pronounced erosion and sedimentation volumes and patterns. In general, SSC levels are larger (up to three times) with SLR (not shown). This is attributed to the larger wave heights (~30%) on the mud flat when SLR is imposed. The small water depth on the mudflat is the limiting factor for wave growth. Larger depths will thus lead to higher waves. Both runs with and without SLR show significant erosion on the eastern mudflat (Figure 23). Assuming that the mud flat profile would be in near-equilibrium conditions when representative, current forcing conditions are applied, we conclude that we overrated the characteristic wind field (and wave conditions) and/or that the mud characteristics need adjustment. For example, mud flocs with a high fall velocity may settle on the bed during calm conditions, but may be re-suspended during windy conditions, albeit with a different fall velocity. Including SLR leads to a higher bed level on the mud flat. This is remarkable. A possible explanation is that SLR allows larger waves in the model domain because they are less limited by depth. The larger wave-induced shear stresses under the SLR scenario not only increase erosion rates but also, because erosion produces higher suspended concentrations, increased deposition rates.

The south and north marsh area tend to erode (apart from some minor sedimentation in the salt marsh channels), whereas the central Marsh area accretes. This remarkable difference is attributed to the fact that the central marsh is about 1 meter higher than the north and south marsh. Waves can easily penetrate and develop on the South and North marsh areas, thus increasing local shear stresses and inducing erosion. Note that this increased susceptibility can be expected due to sea level rise, which yields the same effect as the initial bed elevation being lower. Waves break in front of the central marsh and increase SSC in front of the marsh enabling high concentration tidal flows to transport the suspended sediment towards the central marsh area where it deposits.

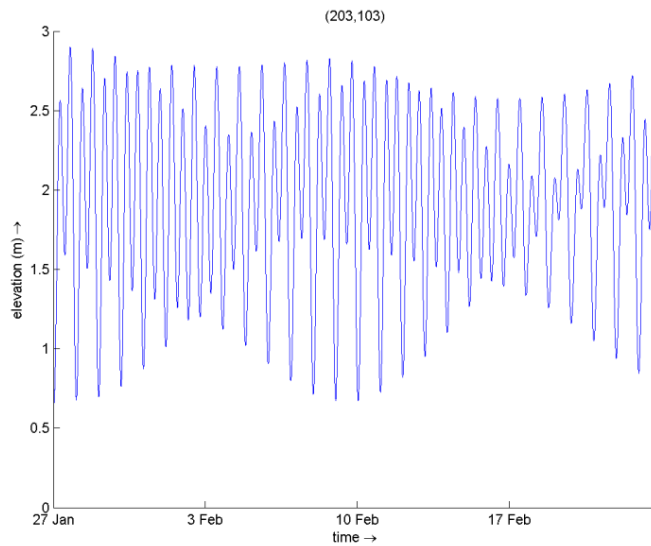


Figure 20 Water level variations during the morphodynamic run.

Sediment from the Creek hardly reaches the mudflat (Figure 24(a, b)). The model runs show that nearly all sediment deposits in the access channel and that (very) minor volumes enter the North marsh area. Bay sediment deposits mainly near the easterly boundary although some sediment reaches the marsh as well and there is more marsh-ward intrusion of Bay sediment for the case of SLR (Figure 24(c, d)). Sediment that is re-suspended from the mudflat is the main source of sediment being transported towards the marsh.

We hypothesize that the sediment on the Corte Madera mudflat mainly originated from the Sacramento catchment as the result hydraulic mining between 1856 and 1884. This sediment is still released by gradual erosion of mining deposits in the Delta, Suisun Bay and San Pablo Bay [Jaffe et al., 2007]. The sediment that currently enters the marsh area originates from the mudflat and, to a very limited extent, also directly from the Bay. Creek sediment hardly contributes to marsh deposition volumes. (Future) SSC levels near the marsh (that are important for marsh accretion rates) are largely controlled by wind wave conditions on the mud flat directly in front of the marsh and not by sediments from the Creek or Bay. Bay sediment supply has a (very limited) impact on the sediment supply to the mudflat and therefore little impact on the mudflat level and SSC over the mudflat over the longer term.

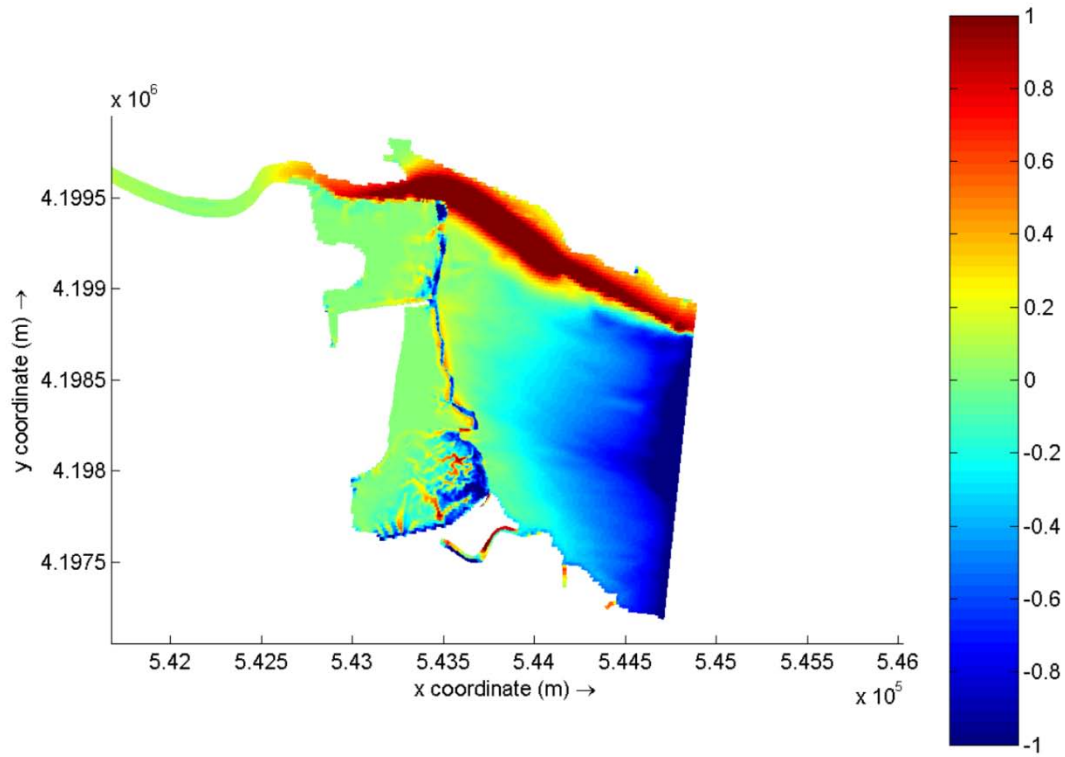


Figure 21 Cumulative erosion and sedimentation after 1 month excluding sea level rise (m)

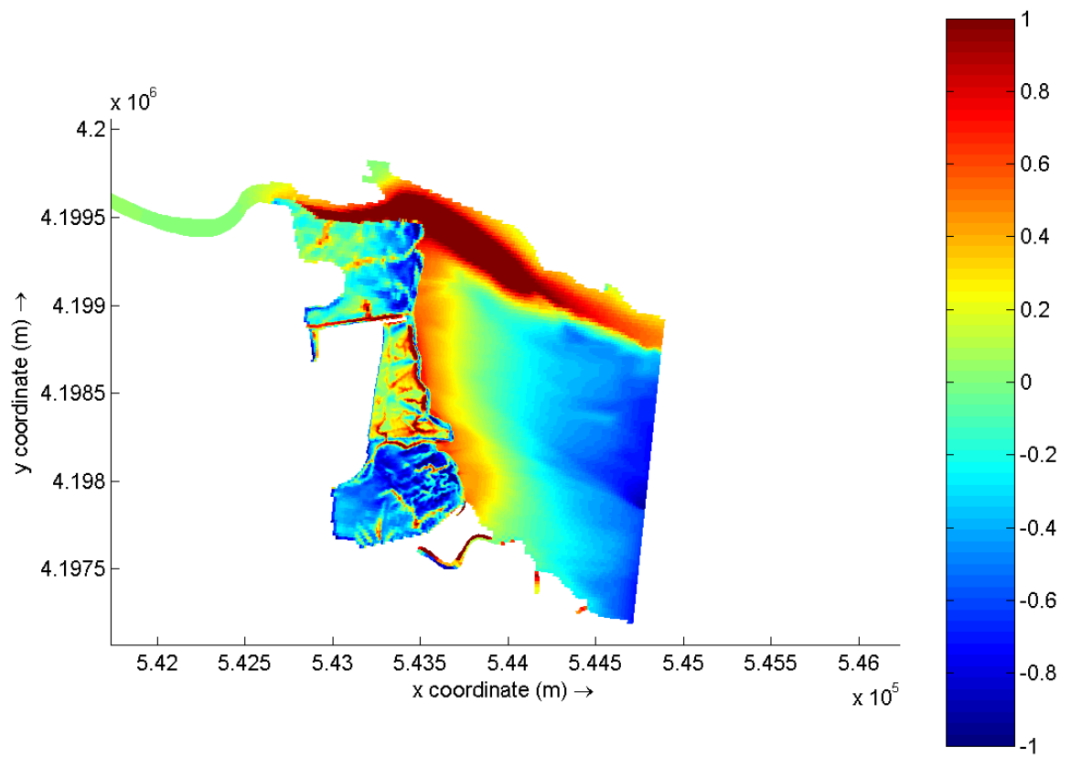


Figure 22 Cumulative erosion and sedimentation after 1 month including sea level rise (m)

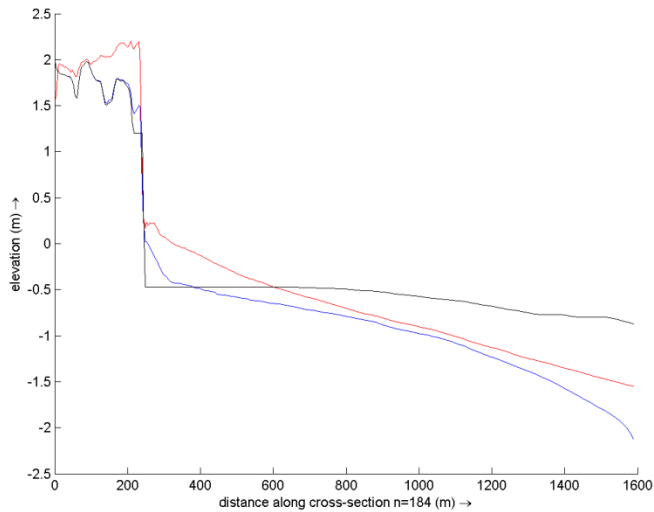


Figure 23 Initial bed level (black line); Bed level after 1 month excluding SLR (blue line) and including SLR (red line).

2.3.3. Discussion

The morphodynamic model results are preliminary. They give insight into possible erosion and sedimentation mechanisms but the (rough) schematization also puts limitations on the accuracy and validity of the results. In this section we present a number of aspects that provide the basis for future, advanced morphodynamic runs.

The mudflat profile is a major factor governing wave heights. This profile in combination with SSC and (future) salt marsh accretion rates, will control morphological evolution of the marsh and its ability to buffer upland flooding. Successful morphodynamic modeling efforts would thus require a model that is able to reproduce a (near) equilibrium profile that resembles the current profile. Sensitivity analysis is required on the sediment characteristics as well as on the SSC at the seaward boundary to reproduce a realistic equilibrium profile.

Imposing SLR by simply adding 1 m of extra water depth is not realistic. SLR levels of this value may be reached within 100 or 200 years from now, or sooner. By that time the mudflat and marsh would have adjusted already to governing conditions. Much longer (time consuming) runs that allow for more gradually imposing SLR would allow adjustment of the morphology to changing conditions, thereby providing more realistic results. However, these runs would be limited in accuracy by unknown and uncertain SSC boundary conditions at the eastern Bay side.

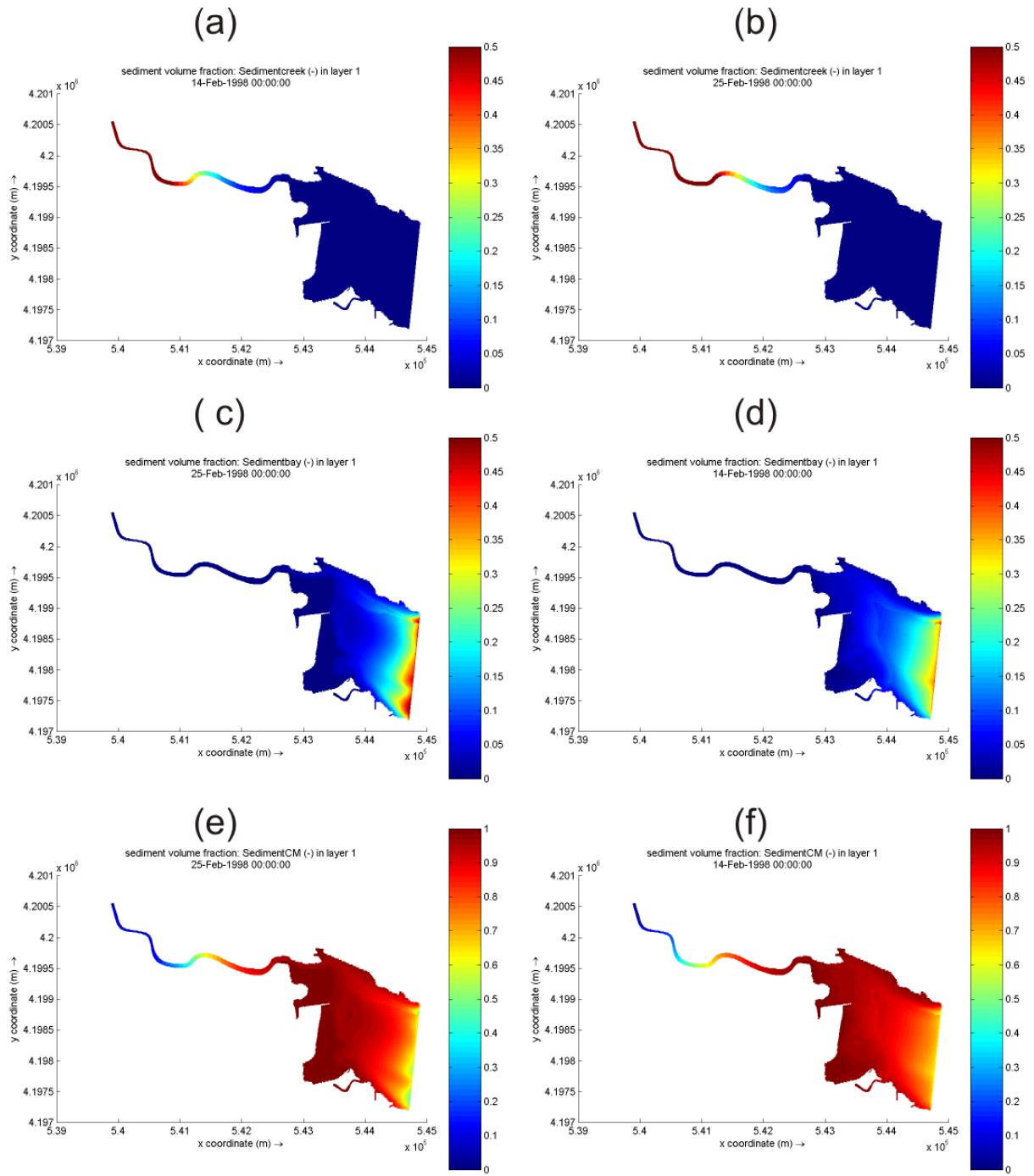


Figure 24 Bed sediment composition after 1 hydrodynamic month (12 morphodynamic months). (a,b) Creek sediment; (c,d) Bay sediment; (e,f) CM sediment; (a,c,e) no SLR (b,d,f) including SLR

3. Conclusions

It is difficult to assess the impact of sea level rise on future characteristic wave conditions on the Corte Madera salt marsh. The main reason is that it is difficult to define extreme conditions in the absence of a full probabilistic analysis of future conditions. Furthermore, morphodynamic developments of the salt marsh and mudflat are uncertain and depend on external forcing such as sediment supply from the watershed and North Bay. Instead we present a sensitivity analysis that indicates the potential impact of key parameters, i.e. water level, wind velocity, vegetation cover, the presence of levees, mudflat accretion and salt marsh accretion.

In the shallow areas of Corte Madera wetland, waves dissipate their energy mainly by bed friction and vegetation. The presence of vegetation has a significant impact on wave heights on the salt marsh. The wave height on the landward salt marsh end is determined by local conditions of wind, water depth and vegetation cover, whereas the wave height at the marsh/mudflat interface is of minor importance to the wave height at the landward end.

Preliminary morphodynamic model runs show erosion and sedimentation patterns in which the central marsh area accretes and the southern and northern areas erode because they are lower than the central marsh area. Major deposition occurs in the access channel. Sediments provided by the Creek or the Bay have a limited impact on the mud flat and salt marsh development. Morphodynamics are governed largely by reworking and redistribution of sediment from the Corte Madera mudflat. More reliable and accurate model predictions of marsh and mudflat changes related to SLR and wind conditions can be obtained with additional sensitivity analysis and longer runs.



Figure 25 View of Corte Madera salt marsh; returning home...

References

- Lacy, J.R., and Hoover, D.J., (2011), Wave exposure of Corte Madera Marsh, Marin County, California—a field investigation: US Geological Survey Open-File Report 2011-1183, 28 p. [<http://pubs.usgs.gov/of/2011/1183/>].
- Van der Wegen, M., B. E. Jaffe, and J. A. Roelvink, (2011), Process-based, morphodynamic hindcast of decadal deposition patterns in San Pablo Bay, California, 1856–1887, J. Geophys. Res., 116, F02008, doi:10.1029/2009JF001614